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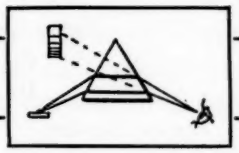

JULY
1934


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Journal of the
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# A Reflectometer for All Types of Surfaces

FRANK BENFORD, *Research Laboratory, General Electric Company, Schenectady, New York*

(Received May 11, 1934)

## INTRODUCTION

IN 1912 P. G. Nutting described[1] a type of reflectometer that depended for its optical action upon the theory of reflection of light between two infinite parallel planes. The instrument employed a nickeled cylindrical mirror to extend, by multiple image reflections, the test plane and illuminating plane to infinity. The losses of light on the mirror were large and the successive images became dimmer as the reflections multiplied, and this departure from uniformly bright planes caused errors that ranged from 10 percent for diffusing surfaces to 30 percent for specular surfaces. The errors for surfaces of a mixed character would fall between these limits, with no ready way of making a working correction.

It was not until A. H. Taylor brought out his reflectometer[2, 3, 4] for the determination of diffuse reflection factors that accurate data on some of the more common diffusers became available.

Another successful attack on the problem was made by W. H. Little,[5] who measured the brightness of the interior of an integrating sphere at a point illuminated by a small zone of initial illumination, and then measured the sphere brightness at a point shielded from the zone. A computation of the coefficient of the sphere surface was made from these two readings, and the test surface was then observed when in the shielded position. The method yields accurate data, but it requires a large sphere to avoid errors arising from the absorption of light by the sample under test.

In 1920 the writer built and described a reflectometer of the "absolute" type.[6] It was composed simply of a spherical surface that was made up of removable sections each equal to one-sixth of a sphere. The spherical surfaces were coated with the material to be tested, and the brightness of the part-sphere, where illuminated only by internally reflected light, was observed for two different assemblies of parts, into, for example, four-sixths and five-sixths of a sphere. Calling the two photometer readings $P_4$ and $P_5$, the coefficient $k$ was directly computed from the formula

$$k=(P_5-P_4)/(\tfrac{5}{6}P_5-\tfrac{4}{6}P_4).$$

[1] P. G. Nutting, *A New Method and Instrument for Determining the Reflecting Power of Opaque Bodies*, Trans. Ill. Eng. Soc. **7**, 412 (1912).

[2] A. H. Taylor, *Measurement of Diffuse Reflection Factors and a New Absolute Reflectometer*, Sci. Papers, Bur. of Standards **16**, 421 (1920).

[3] A. H. Taylor, *A Simple Portable Instrument for Measuring Reflection and Transmission Factors in Absolute Units*, Trans. Ill. Eng. Soc. **15**, 811 (1920).

[4] A. H. Taylor, *A Simple Portable Instrument for the Measurement of Reflection and Transmission Factors*, Sci. Papers, Bur. of Standards **17**, 1 (1922).

[5] W. H. Little and C. H. Sharp, *Measurement of Reflection Factors*, Trans. Ill. Eng. Soc. **15**, 802 (1920).

[6] Frank Benford, *An Absolute Method for Determining Coefficients of Diffuse Reflection*, Gen. Elec. Rev. **23**, 72 (1920).



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The instrument had the common defect of functioning properly only for diffusing surfaces, and if the test surface showed any trace of gloss the determinations were presumed to be inexact. It is the only instrument mentioned in this paper that is "absolute" in the sense of being independent of all other photometric standards. The two necessary conditions in the instrument are accurate divisions of the sphere and an accurate photometer scale, which need not be calibrated to read any of the photometric units.

Enoch Karrer, in 1922, made an extended mathematical analysis of the problems of reflectometry[7] and widened the field of usefulness of the reflectometer, but his instrument was still limited to diffusing surfaces, and up to the present time the surface that reflects by a mixture of specular and diffuse action has not had a portable instrument for its accurate measurement.

The mathematical methods here employed have been found to be useful tools in the previous work with part-spheres, both for photometry and reflectometry, and the analytical work is greatly simplified by the small number of variables involved in the equations. The analysis covers several possible constructions of the new instrument, for variable working conditions may make preferable other constructions than the one here selected.

## General Theory

The theory of a part-sphere reflectometer differs from that of a complete sphere on account of the presence of a flat surface, the test surface, that cannot exchange light between its various parts in the manner in which a point on the sphere illuminates all other parts of the sphere. Light from one section of the test surface can illuminate another section only after an intermediate reflection from the spherical surface.

The method of attack here employed consists of tracing the successive exchanges of light between the active surfaces and then summing up the resultant finite series, which are infinite in number.

[7] Enoch Karrer, *Use of the Ulbricht Sphere in Measuring Reflection and Transmission Factors*, Sci. Papers, Bur. of Standards **17**, 415 (1922).

Let $F_0$ = the light entering the instrument
$m$ = coefficient of reflection of the sphere surface
$x$ = coefficient of reflection of the aperture surface
$a$ = fraction of sphere cut off by aperture
$s$ = fraction of sphere remaining.

The series given below represents the successive reflections of light and their summations therefore give the brightness of the surfaces, after the summation has been divided by the area involved. This latter step is omitted throughout because relative values are of more interest than actual values, and the simplified equations are somewhat easier to handle.

At each reflection of light from the part-sphere the light is divided in the exact ratio of the spherical area $s$ and the spherical area $a$ cut off by the plane of the aperture, and therefore on the next reflection this particular quantity of light is multiplied by the factor $ms+ax$. The light reflected from the test surface goes in its entirety to the spherical surface and on reflection there amounts to simply $m$ times its previous value. Each term of the sphere series, multiplied by $ms$, gives a new sphere term, and each term of the corresponding aperture series, multiplied by $m$, also gives terms for the next sphere series.

Starting with a quantity $F_0$ of light incident upon some restricted area of the spherical surface, we get the following expansions:

| *Reflected from sphere* | *Reflected from aperture surface* |
|---|---|
| $F_0m$ | 0 |
| $F_0m(ms)$ | $F_0m(ax)$ |
| $F_0m(m^2s^2+amx)$ | $F_0m(amsx)$ |
| $F_0m(m^3s^3+2am^2sx)$ | $F_0m(am^2s^2x+a^2mx^2)$ |
| $F_0m(m^4s^4+3am^3s^2x+a^2m^2x^2)$ | $F_0m(am^3s^3x+2a^2m^2sx^2)$ |
| $F_0m(m^5s^5+4am^4s^3x+3a^2m^3sx^2)$ | $F_0m(am^4s^4x+3a^2m^3s^2x^2+a^3m^2x^3)$ |
| etc. | etc. |

An inspection of the quantities in the parentheses taken in vertical columns shows the numerical coefficients to make arithmetical series of the 0, 1, 2, etc., order, and the other terms are either constants or part of a geometrical series. Also the terms at the heads of the columns, except the first in the sphere series, form a

geometrical series with a ratio $amx$. Omitting the original term $F_0m$, because the point of initial illumination will not be selected for photometric observation, the columns sum up as follows for the light $F_1$, from the spherical surface,

$$F_1 = F_0 m\left[\frac{ms}{1-ms}+\frac{amx}{(1-ms)^2} + \frac{a^2m^2x^2}{(1-ms)^3}+\frac{a^3m^3x^3}{(1-ms)^4}+\cdots\right]$$

$$=\frac{F_0m^2(s+ax)}{1-ms-amx} \qquad (1)$$

and for the light $f_1$ from the test surface

$$f_1 = F_0amx/(1-ms-amx). \qquad (2)$$

In designing a reflectometer one of the most important points is the integrating sensitivity, $S$, that may be expected when measuring surfaces near the upper and lower limits of reflectivity. Defining the sensitivity as

$$S=(x/F)(dF/dx) \qquad (3)$$

the equations for $F$ and $f$ can be used to explore for the optimum working conditions.

## Optimum Conditions

In arranging the illumination of the reflectometer and the placing of the photometer for the observation of the brightness of some section, there are several possibilities to be considered. The point of initial illumination may be either on the sphere, or the aperture surface, but it should not be the identical point observed for brightness because the distribution of light in the spot cannot be controlled and its brightness is not a true measure of the quantity of light being reflected, and at least one reflection is required before the light is properly diffused throughout the instrument. There are four possibilities that should be investigated:

(1) Sphere illuminated, sphere observed.
(2) Sphere illuminated, aperture surface observed.
(3) Aperture surface illuminated, sphere observed.
(4) Aperture surface illuminated, aperture surface observed.

These conditions can be investigated by the use of Eq. (3) with such changes as are called for by the four variations.

The size of the aperture also should be investigated for the best working conditions, and this involves the very practical consideration that the surfaces submitted for test are often small, particularly when they are for precise optical purposes. It, therefore, seems advisable to keep the aperture to some small upper limit, say two inches in diameter, and the size of the sphere can then be determined for best integrating conditions.

### (1) Sphere illuminated, sphere observed

When Eq. (1) is differentiated with respect to $F_1$ and $x$ and the substitution is made in Eq. (3), the sensitivity is found to be

$$S_1 = ax/[(s+ax)(1-ms-amx)]. \qquad (4)$$

In Fig. 1 this equation is plotted for three apertures, $a=0$, 0.25 and 0.50. It is seen that in general the sensitivity is low, and while the largest aperture gives the best sensitivity, it is only for surfaces having a coefficient of over 0.50 that the sensitivity is better than unity.

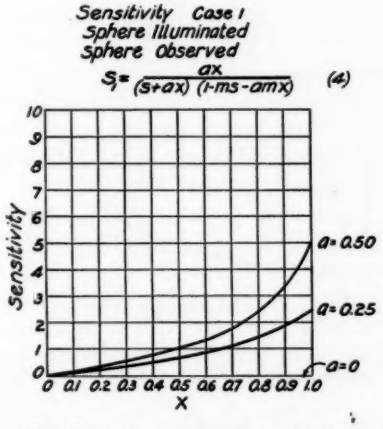


Fig. 1. The factor by which changes in the coefficient of the aperture are multiplied in the photometer reading is a function of $a$ and $x$ as illustrated.

The coefficient $m$ is taken as 0.90 in computing Fig. 1. The actual surface, magnesium carbonate, has a coefficient 0.98, but the two apertures for the admission of light and for observation reduce the effective coefficient to about the value used.

**(2) Sphere illuminated, aperture surface observed**

As the surface of the aperture is here to be observed in the photometer field, the summation of the reflected light, as given by Eq. (2), is a measure of the brightness, and applying to this equation the operation of Eq. (3) we get for the integrating sensitivity,

$$S_2 = 1 + amx/(1 - ms - amx) \qquad (5)$$

and it is at once evident that the sensitivity is always greater than unity. If the photometric determination can always be made as close as some fixed limit, say one percent, then the sensitivity of the reflectometer will always be better than one percent, and this arrangement of the instrument is better when working with surfaces of low reflectivity, as is illustrated by comparing Fig. 2 with Fig. 1.

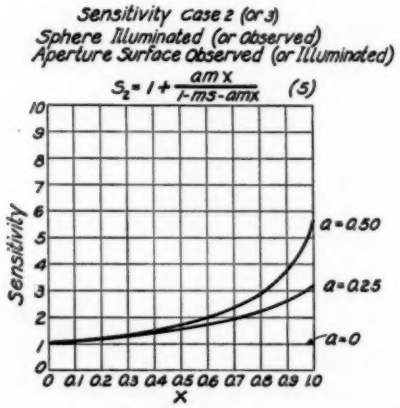


FIG. 2. These two arrangements of the instrument give a photometric sensitivity that is always greater than unity.

**(3) Aperture surface illuminated, sphere observed**

When the entering light is incident upon the aperture surface, the first terms of the finite series become:

| *Reflected from sphere* | *Reflected from aperture surface* |
|---|---|
| 0 | $F_0x$ |
| $F_0mx$ | 0 |
| $F_0mx[ms]$ | $F_0mx(ax)$ |
| $F_0mx[m^2s^2+amx]$ | $F_0mx(amsx)$ |
| etc. | etc. |

The first effective term is $F_0mx$, and the summation of all series on the left gives

$$F_3 = F_0mx/(1 - ms - amx) \qquad (6)$$

and the integrating sensitivity is

$$S_3 = 1 + amx/(1 - mx - amx), \qquad (7)$$

which is identical with the sensitivity of Case 2.

**(4) Aperture surface illuminated, aperture surface observed**

If the instrument is so designed that one part of the aperture surface receives the initial illumination, and a distinct part of the aperture surface is observed for brightness, then the determinations will be independent of the precise manner in which the initial illumination is distributed. The first term of the aperture surface series is $F_0mx(ax)$ in place of $F_0m(ax)$ and in place of Eq. (2) we have

$$f_4 = F_0amx^2/(1 - ms - amx). \qquad (8)$$

The sensitivity equation is

$$S_4 = 2 + amx/(1 - ms - amx). \qquad (9)$$

This is the best of the four conditions for integrating sensitivity (see Fig. 3) but there is

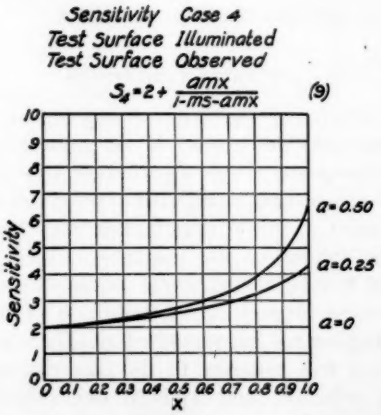


FIG. 3. This construction of the reflectometer gives a sensitivity that is always greater than 2.

the question of the lack of symmetry in the illumination produced by having the initial spot off center.

An inspection of the sensitivity curves for the four possible arrangements of the points of illumination and observation shows that the first

case is decidedly inferior and that case 4 is much better than either case 2 or case 3, which are identical. There are certain optical difficulties involved in both illuminating and observing the aperture plate, for the two points must be kept distinct with no possibility of a transfer of light from the illuminated spot to the spot being observed. Also there probably would be difficulty in securing a sufficiently uniform distribution of light if the spot of initial illumination is anywhere except at the center of the aperture plate. For the present, where a small sized instrument is desired, case 4 has not been experimentally investigated and attention has been confined to case 3, which was chosen rather than case 2 because observing the sphere wall insures a good photometric field, which might not be the case if the aperture plate is observed, particularly when testing a surface that is non-uniform in character.

## Design of Reflectometer

The spherical part of the reflectometer is composed of two blocks of magnesium carbonate in which hemispherical cavities have been bored. The two blocks are assembled in a $3\frac{1}{2}$ inch by $3\frac{1}{2}$ inch hardwood case, and the tops of the blocks are cut off level to sufficient depth to give the desired size of aperture. The case is closed by a brass cover having a central hole to hold the aperture plate in coincidence with the opening into the sphere. (Fig. 4.)

Means are provided for attaching the reflectometer to a direct vision photometer so that the brightness of a spot on the equator of the sphere can be balanced in the photometric field.

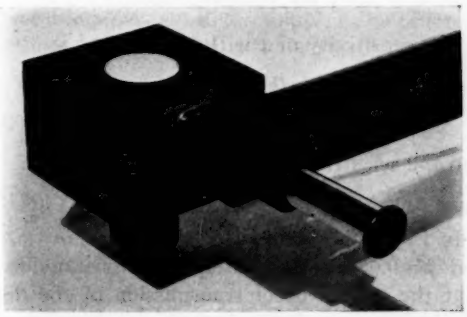

Fig. 4. The reflectometer attached to a direct vision photometer.

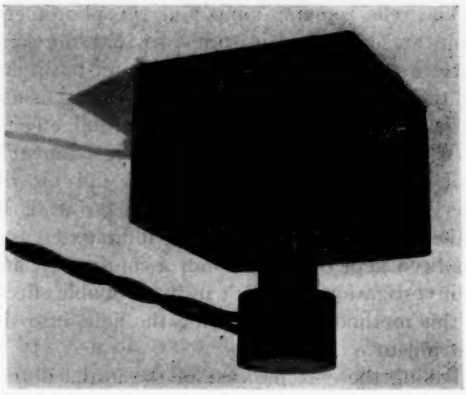

Fig. 5. Bottom of reflectometer showing adjustable lamp housing.

In the equations so far considered there is implicitly the condition that all surfaces are perfect diffusers. Relatively few of the ordinary surfaces can even approximate this condition, and a reflectometer to be of general use must either avoid or bridge this gulf. In the present instrument it has been bridged by the expedient of reducing all surfaces to approximately perfect diffusers. This is accomplished by placing in the aperture a thin disk of etched glass. The test surface is placed over this diffuser, and the light that is reflected back into the instrument has approximately the same spatial distribution regardless of the nature of the test surface.

The aperture plate is a piece of optically clear glass 1 mm thick, and acid etched on both sides. It was found necessary to have the etching deep, and to use both surfaces in order to get sufficient diffusion to reduce the reading on a mirror to the value given by an image test at 45 deg., this angle being selected for reasons to be given later.

The source of illumination is one of the photometer lamps provided for the illuminometer which was used in this development. This lamp is carried in an adjustable housing attached to the bottom of the reflectometer, and the light passes through a small circular diaphragm and illuminates a spot about one cm in diameter in the center of the aperture plate. By moving the lamp in its housing, the amount of light entering the instrument can be controlled, and thus any desired part of the photometer scale can be used. (Refer to Fig. 5.)

The reflectometer lamp and the photometer lamp are connected in series, so that the same batteries, ammeter, etc., will serve for both, and as the lamps are of the same rating, small variations in current are without visible effect.

A fundamental condition of the instrument is that all the entering light shall fall on the aperture plate and none on the sphere wall. To make sure of this condition, the illuminated area has been kept down to about a centimeter, and an investigation was made of the probable effects of this method of introducing the light into the instrument.

Taking the extreme case of the initial illumination being concentrated at the center of the aperture, the illumination, $E_\beta$, on the sphere wall for $\pi$ lumens reflected from the aperture plate is

$$E_\beta = \frac{(Q - R\cos\beta)(R - Q\cos\beta)}{(R^2+Q^2-2RQ\cos\beta)^2}, \qquad (10)$$

where $R$ is the radius of the sphere,
$Q$ is the distance from the center $O$ of the sphere to the center of the disk,
$\beta$ is the angle between $Q$ and the radius to the point of illumination on the sphere.

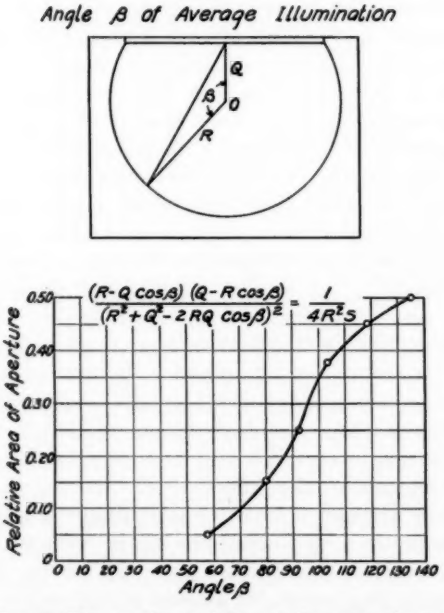


FIG. 6. The angular position of the zone of average sphere illumination by a radiating point in the center of the aperture is given by the curve for various sizes of apertures.

If the same quantity of light is given off by the entire surface of the diffusing disk, then the resultant first illumination of the sphere is uniform in all parts, and for $\pi$ lumens from the disk,

$$E = \pi/4\pi R^2 s = 1/4R^2 s. \qquad (11)$$

In order that the nonuniform illumination due to the concentration of the light at the center of the aperture may not influence the photometer reading, the point of observation should be at the point where the illumination computed by Eq. (10) equals that computed by Eq. (11).

A simultaneous solution of the two gives the angle $\beta$ for equality of illumination as shown in Fig. 6 for apertures from 0 to 0.50. It is evident from the curve that $\beta = 90$ deg., that is, the equator of the magnesium sphere gives the best point of observation, and the three experimental instruments here mentioned have all been so constructed.

The instrument with a diffusing disk in the aperture evidently measures the coefficient of the combination of the aperture disk and test surface. Let the disk have the following coefficients:

$r$ = coefficient of reflection
$p$ = coefficient of transmission
$a$ = coefficient of absorption

so that

$$r + p + a = 1 \qquad (12)$$

and let

$x$ = coefficient of reflection of combined disk and test surface, and
$k$ = coefficient of reflection of test surface.

The relation between $p$, $k$, $r$ and $x$ is

$$x = r + p^2k + p^2k^2r + p^2k^3r^2 + \cdots$$
$$= r + p^2k/(1-kr). \qquad (13)$$

The sensitivity of $x$ with respect to $k$ is

$$S' = kdx/xdk$$
$$= kp^2/[(r - kr^2 + p^2k)(1-kr)] \qquad (14)$$

and the sensitivity of the instrument is

$$S'' = SS' = kdL/Ldk. \qquad (15)$$

In Fig. 7 the value of $S'$ is given for $r = 0.21$, and $p = 0.66$. From the equation it is evident that the coefficient of transmission of the disk should be a maximum in order to attain high instrument sensitivity. For low coefficients $k$ of

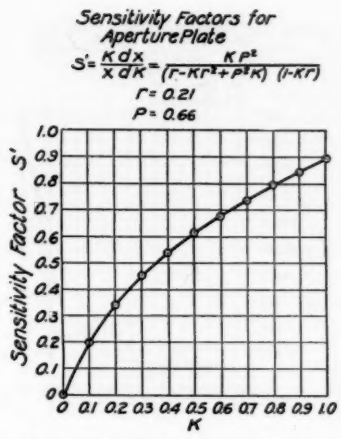


FIG. 7. The material and density of the aperture plate influence the photometric sensitivity of Figs. 1, 2 and 3 by the factors given above, and the sensitivity of the complete reflectometer is as shown in Fig. 14.

the test surface, the use of the disk greatly lowers the sensitivity of the instrument, but by choosing the second, third, or fourth arrangements in preference to the first, the sensitivity may be kept high enough for routine work. Fig. 14 gives the net integrating sensitivity of a complete reflectometer having $a=0.1465$, $s=0.8535$.

## CALIBRATION

It is, of course, not possible to construct an instrument of the nature of this reflectometer in such a way that it will not change with time and use, and therefore ready means should be at hand for calibration. There are at least two dependable standards that are always available. (Fig. 9.) One is magnesium carbonate, which may be obtained in block form at the drugstore. Several independent determinations, by different methods, have consistently yielded values of

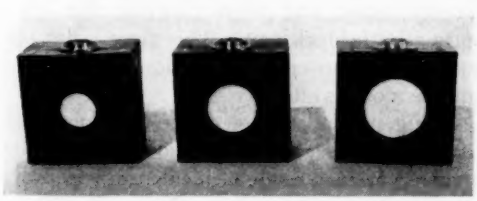

FIG. 8. Three experimental reflectometers having angular apertures of 60 deg., 90 deg., and 120 deg., and values of $a$ equal to 0.0670, 0.1465 and 0.2500, respectively.

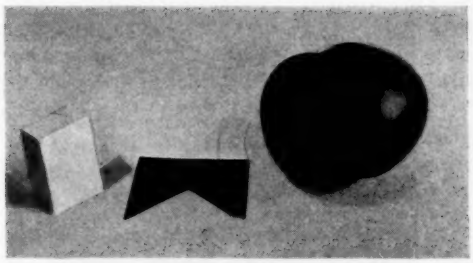

FIG. 9. Three calibration standards having coefficients of 0.98, 0.06 and zero.

reflectivity between 0.97 and 0.99, and an average value of 0.98 is here used as one of the two basic figures.

The second standard is a hollow metal cone, having the form of an acorn, painted a dead black inside and so constructed that only a small fraction of light entering the cone can be returned through the opening by internal reflections. The coefficient of reflection of this cone is practically zero, and it is assumed, for calibration purposes, that it is actually zero.

An auxiliary standard is the black paper that is used for wrapping photographic negatives. This paper is not invariable, but if the reflection coefficient of a sample is determined by some independent means (such as a reflectometer of the Taylor or Karrer form), it can be used to find a number of additional points on the calibration curve of the reflectometer.

On the metal cover plate of the reflectometer a number of radial lines are scribed converging on the center of the aperture. By the aid of these lines a piece of the black paper can be placed so as to cover half of the aperture, and the remainder of the aperture can then be covered with a block of magnesium carbonate. (Fig. 10.) The coefficient of the composite surface is the average coefficient of the two, or about 0.52. The paper should be moved around in 90 deg. steps so as to avoid errors arising from dissymmetry of the spot of initial illumination, and the average thus found. Various combinations of the two surfaces can be used, such as a 90 deg. or a 270 deg. sector of paper. With only the zero cone, paper and magnesium carbonate, six points are found at 0, 0.06, 0.29, 0.52, 0.75 and 0.98, and these points are well located for

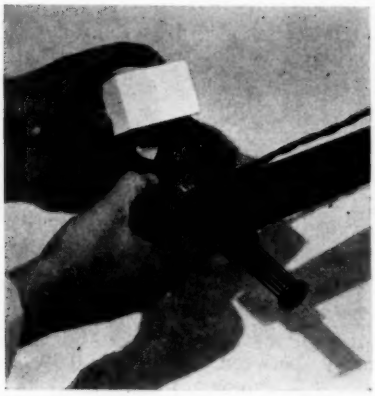

FIG. 10. The aperture plate has three-quarters of its area covered with black paper and with the magnesium carbonate block over the remaining quarter the test coefficient will be 0.29.

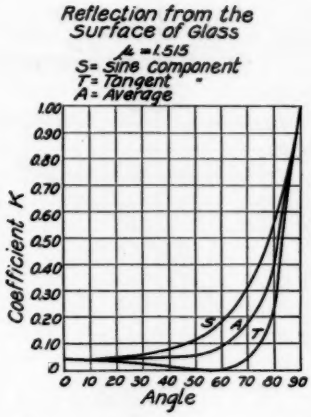


FIG. 11. The manner in which the surface of glass reflects unpolarized light at various angles of incidence is given by curve *A*.

an accurate drawing of the complete calibration curve.

This method of using two standardized surfaces to get intermediate coefficients is limited in accuracy only by the errors of placing the paper over the aperture, and with care the errors introduced by lack of perfect placing should be small, and a calibration curve so derived should be free from variations that might be encountered if a larger number of independent standards are used to get a sufficient number of points to draw a well-established calibration curve.

It has been customary during the experimental work to complete the calibration by testing several glass and metal mirrors of known characteristics, but here it seems desirable to discuss briefly the dependence of the coefficient of a specular surface upon the manner of illumination.

In Fig. 11 the coefficients of a single glass surface are shown for the two polarization components as computed by Fresnel's equations. The average coefficient is seen to rise slowly from 0.0418 at normal incidence to 0.0522 at 45 deg. and then more rapidly to 1.000 at grazing incidence. Under diffused illumination, that is, light from a uniformly bright hemisphere covering the surface, the total amount of reflected light from a single glass surface has been computed to be 0.090 of the incident light. This variation with the distribution of the incident light holds in some degree for every surface, as may be seen by inspecting any good diffusing surface near the grazing angle. There will be found a considerable amount of specular action, and this indicates a tendency toward a high coefficient at the limiting angle. This brings up the question: What is the coefficient of such a surface? and the answer can best be found by considering the ways in which the surface might be used in service.

Specular reflectors as a rule are used for light incident within 60 deg. of the normal, and the average angle is perhaps much less. In precision types of searchlight mirrors the maximum angle of incidence is 30 deg., while in floodlights the angle may reach 60 deg. In optical instruments 45 deg. is often used. A survey of uses to which specular surfaces are put will show but few cases of use over the entire hemisphere, and therefore an effort has been made to construct the reflectometer so that it will give a figure representative of the useful angle of the surface.

A one-surface specular standard was made by acid etching one surface of a thin piece of good quality glass, and then painting the etched surface with black paint. This gives a flat black surface with no visible reflection, and the front surface alone is effective.

In Fig. 12 the average of the two polarization components, weighted for the area of hemisphere involved at each angle of incidence, is shown as integrated from zero to angles up to 90 deg. The average coefficient for the parallel component in Fig. 11 is 0.1490, and for the perpendic-

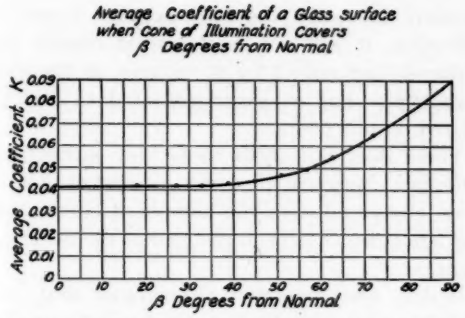


FIG. 12. The manner in which the average coefficient of reflection of a glass surface changes with the cone of illumination has an important bearing on all tests of surfaces having specular characteristics.

ular component 0.0317, giving an average of 0.0903 for both, as indicated by the maximum of the curve in Fig. 12.

If the useful angle is limited to 60 deg. from the normal, the average coefficient is 0.052. It is thus evident that this simple glass surface may have a number of coefficients of reflection, depending upon how it is tested, or how it is to be used. For the present, at least, the specular coefficient at 45 deg. from the normal has been adopted by the writer as giving a useful average value, and the data on specular coefficients of mirrors given later have all been taken at this angle.

This one-surface piece of glass has a computed specular coefficient of 0.052 at 45 deg. and an average coefficient of 0.052 for diffused illumination up to 60 deg. from the normal. The reflectometer read 0.050, which is in agreement with the two figures just given, rather than with the coefficient of 0.090 for hemispherical illumination.

The difference of 0.04 has appeared a number of times during the experimental work. A glass mirror having a specular coefficient of 0.93 at 45 deg. has been read as 0.96 to 0.97 when the reflectometer was used in the condition of case 1 previously described, and another metal mirror tested 0.81 by specular action, 0.81 by the finished reflectometer here described, and 0.86 by tests at another laboratory with an instrument similar to case 1.

The higher values, while probably correctly representing the physical facts, do not give data that apply to any use to which the mirror may be put, and it is felt that the lower values given with a proper density of the diffusing aperture disk will apply directly to practically all optical and engineering applications.

The calibration curve of the reflectometer has been computed for the construction of case 3:

$s = 0.8535$
$a = 0.1465$
Angular aperture $= 90°$
Photometer reading for $k = 0$, $= 3.23$
Photometer reading for $k = 0.98$, $= 20.19$.

The instrument was first calibrated by means of the "zero" cone, magnesium carbonate, and black paper, and the calibration curve for *diffusing surfaces* drawn.

A duplicate diffusing disk was placed over the one in the aperture of the instrument, and its coefficient of reflection was found to be 0.21 when backed by the "zero" cone. When backed by magnesium carbonate the coefficient of the combination of disk and $MgCO_3$ did not rise to 0.98 as would occur if there was no loss in the test disk. The indicated reflection was 0.75 and substituting in Eq. (13) the value of the transmitted light is computed to be 0.66 of the incident light. The total light accounted for is $0.21 + 0.66 = 0.87$, leaving 0.13 as the absorption loss.

## TEST DATA

The writer is indebted to Mr. John E. Bock for taking most of the data for the calibration and critical testing of the three experimental reflectometers (Fig. 8) with openings of 60 deg., 90 deg., and 120 deg. ($a = 0.067$, 0.1465 and 0.25, respectively), and in particular for much of the data given in Fig. 13 on the 90 deg. instrument.

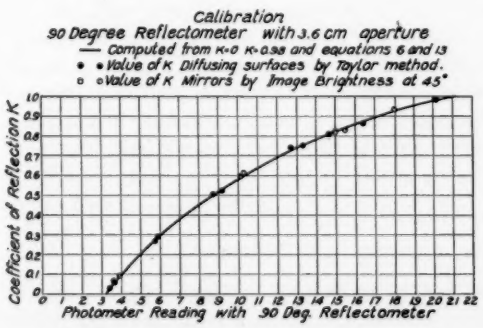
Calibration
90 Degree Reflectometer with 3.6 cm aperture
— Computed from K=0 K=0.98 and equations 6 and 13
• • Value of K Diffusing surfaces by Taylor method.
o o Value of K Mirrors by Image Brightness at 45°
Coefficient of Reflection K
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Photometer Reading with 90 Deg. Reflectometer

FIG. 13. The degree of agreement between the tests on diffusing surfaces (dots) and mirrors (circles) is taken as the criterion of the reflectometer design.

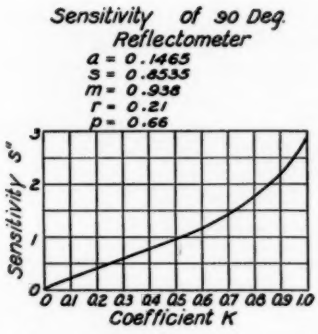


FIG. 14. The sensitivity of the complete reflectometer is given by the curve, which was computed from the given values of $a$, $s$, $m$, $r$ and $p$ substituted in Eqs. (5), (14) and (15).

The solid points in Fig. 13 are for diffusing surfaces whose coefficients $k$ were determined by independent methods and they are shown plotted against the photometer reading when using the 90 deg. reflectometer.

The circles are coefficients of pure specular surfaces obtained by comparing the brightness viewed in the mirror at 45 deg. angle of incidence and reflection. The test of the instrument is not how well these points agree with the curve, which is a computed curve, but how well the two sets of test points agree with one another. It is believed that if a given instrument will measure correctly the two extreme types of reflection, it will not be far from correct for surfaces that reflect by a mixture of the two pure types, but no experimental data can be offered on this point.

There does not seem to be any systematic difference between the two groups of points when compared with the computed curve, and this agreement has been the goal of the development.

It has been assumed throughout that the surface being tested is in mechanical contact with the diffusing disk. In the case of a glass or other second surface mirror, the predominant reflecting surface will be separated from the disk by the thickness $t$ of the glass (in inches) and the indicated coefficient may be corrected by multiplying by the following experimentally determined factor,

$$K=1+0.134t+1.66t^2. \tag{16}$$

The good agreement between the theoretical curve and the test points, while, of course, gratifying to the computer, should not be given much weight because the instrument under test was used to determine several of the factors used in making the computation, and the agreement is therefore a necessary but not a sufficient condition.

# The Absorption of Ultraviolet and Visible Light by Water

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(Received May 14, 1934)

The absorption coefficient of chemically pure, fairly dust free water was measured by photographic photometry by using tubes of water up to 272 cm long. $\gamma$, defined by $i=i_0e^{-\gamma x}$, where $x$ is in cm, was 0.8, 1.9, 4.3, 7.7, 13.5 and $80\times10^{-3}$ at wave-lengths 4000, 3600, 3200, 2800, 2400 and 2000A, respectively. The values were more than 10 times those calculated from molecular scattering. For the visible wave-lengths 5400, 5890, 6700 and 6900A $\gamma$ was 0.0004, 0.0014, 0.0034 and 0.0039, in good agreement with the measurements of Aufsess. For wave-lengths from 4000 to 5400A $\gamma$ was less than 0.0004 and was too small to be measured with the length of tubes used.

INVESTIGATIONS of the absorption coefficients of water for light in the ultraviolet region of the spectrum have led to values which differ among the various observers[1, 2, 3, 4] by hundreds of percent. And therefore some uncertainty has existed as to just what the ultraviolet absorption of water really is. In the present experiments the absorption coefficients were determined with an accuracy better than 20 percent for water chemically pure and fairly free from dust.

The apparatus is shown in Fig. 1. A well-defined narrow beam of light from source $s$ passed through diaphragms $e$, $f$ and $g$ with circular holes 0.5 cm in diameter, and thence through the long water cell $h$, or the short one $k$, without touching the sides of the cell to the quartz spectrograph $p$. The cells were on a sliding carriage so that either one in turn could be placed in the path of the beam. They were of Pyrex glass, 4.5 cm inside diameter, with plane parallel quartz end plates $q$. $k$ was 0.3 cm long and the end plates were put on without cement. Two lengths were used for the long tube $h$, one 272 cm long for wave-lengths from 4050 to 2700A, and one 35.5 cm long for wave-lengths from 3020 to 2016A. It being difficult to grind the ends of $h$ accurately perpendicular to the axis of the tube, they were ground approximately so and the quartz plates were pressed by brass collars and three set screws against soft rubber washers, 0.3 cm thick, against the ends of the tube. By means of the set screws the quartz plates could be adjusted parallel to each other and perpendicular to the axis of the tube, the test being that the beam of light pass into, through, and emerge from the tube without deviation or distortion. No lenses were used between $s$ and $p$. The transmissions of a number of quartz plates were tested until four were found which had the same transparency in the ultraviolet.

Distilled water was redistilled in quartz into $h$ at atmospheric pressure, the ebullition being so slow that about 25 hours were required to fill the tube. After repeated rinsing the tubes were filled for measurement. The water was fairly dust free, no large motes were visible, the beam showed a slight Tyndall cone considerably polarized. A Labarc quartz mercury lamp operated from a storage battery served as a source for wave-lengths longer than 2300A and for the shorter wave-lengths a condensed copper spark was used actuated by a 500 cycle alternator supplied from a storage battery. Measurements showed that the intensity of the sources was very constant for 100 minutes, which was longer than the time required for a single set of observations.

The absorption coefficient $\gamma$ for a specified wave-length is defined by

$$i=i_1e^{-\gamma(x-x_1)}, \qquad (1)$$

where $i$ and $i_1$ are the intensities of the light emerging from tubes $h$ and $k$ of lengths $x$ and $x_1$ cm, respectively. $i/i_1$ was determined by the usual method of photographic photometry.

[1] Kreusler, Ann. d. Physik **6**, 412 (1901).
[2] Tsukamoto, Rev. d' Optique **7**, 89 (1928).
[3] Hulburt, J.O.S.A. and R.S.I. **17**, 15 (1928).
[4] Hodgman, J.O.S.A. **23**, 426 (1933).

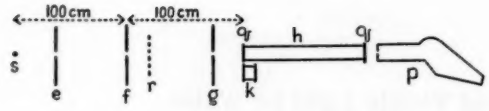


FIG. 1. Apparatus for measuring absorption.

Spectra were taken on the same plate with the same time of exposure of the beam through the long tube $h$, the short tube $k$ and of the beam degraded in a series of known intensities by a rotating sector $r$, Fig. 1. The rotating sector had four openings, the speed of rotation being 120 times a minute, and there was no intermittency effect[5] to disturb the reciprocity law of photographic exposure. The times of exposure ranged from 15 seconds to 10 minutes and were adjusted by trial to be most suitable to each spectral region, so that the lines in the region concerned were neither too strong nor too weak. Curves of each spectrum were made with the recording densitometer from which, omitting tedious and obvious details, the values of $i/i_1$ were determined. From these $\gamma$ was calculated by means of (1).

The average values of $\gamma$ obtained from measurements of 33 plates were plotted as dots in Fig. 2 and smooth curves 1 and 1′ were drawn through them, 1′ being the continuation of 1 with the scale of ordinates enlarged 10 times. The values of $\gamma$ from the smooth curves are in Table I.

TABLE I.

| Wave-length | $\gamma$ | Wave-length | $\gamma$ | Wave-length | $\gamma$ |
|---|---|---|---|---|---|
| 4000A | 0.0008 | 3200A | 0.0043 | 2400A | 0.0135 |
| 3800 | 0.0013 | 3000 | 0.0064 | 2200 | 0.033 |
| 3600 | 0.0019 | 2800 | 0.0077 | 2000 | 0.08 |
| 3400 | 0.0028 | 2600 | 0.0092 | | |

Individual determinations of $\gamma$ deviated sometimes as much as 30 percent from the mean, and the means are probably correct to less than 20 percent. The tubes were refilled with water 4 times, some of the 33 plates were repetitions through the same tube of water. Within the error of experiment $\gamma$ was the same for the various refillings, and did not change when the water remained in the tube from 1 to 3 days. Most important of all, the same values of $\gamma$ were obtained from the two lengths of tube $h$, 272 and 35.5 cm, in the spectral region from 3020 to 2700A where the tubes overlapped.

[5] Webb, J.O.S.A. 23, 157 (1933).

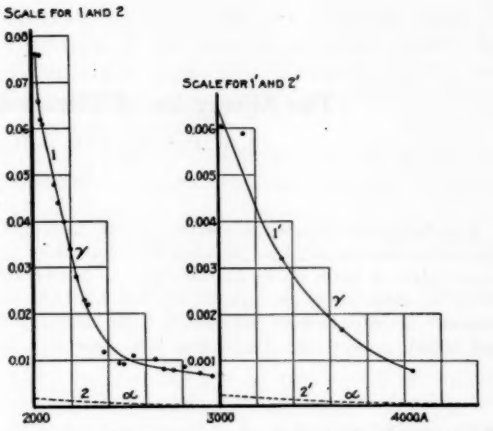


FIG. 2. Ultraviolet absorption coefficient of water, curves 1 and 1′ observed, curves 2 and 2′ calculated from molecular scattering.

The values of $\gamma$ of Fig. 3 agree within 20 percent and less with those of Tsukamoto in the region of the spectrum from 2000 to 2200A, the region which the two sets have in common. In his experiments Tsukamoto used cells from 0.5 to 5 cm in length. In fact, Tsukamoto's values below 2000A, i.e., 4.7, 1.11, 0.86, 0.48, 0.20 and 0.12 at 1829, 1854, 1862, 1878, 1916 and 1935A, respectively, and the values of Fig. 2 or Table I may be regarded as the most accurate available at the present time. It is seen that water is quite transparent to wave-lengths even as short as 2200A, and from our experience it is believed that the wide range of ultraviolet absorption coefficients obtained by earlier observers[1, 3, 4] may be attributed primarily to the use of cells so short that the true water absorption was not revealed amid the inevitable errors of observation. This seems to be more probable than to suppose that the variances were due to impure water or to some unknown factor.

Raman[6] calculated the light absorption coefficient $\alpha$ for water due to molecular scattering to be 0.000022 for wave-length 5220A. Comparing

[6] Raman, *Molecular Diffraction of Light*, page 54 (1922), Calcutta University Press.

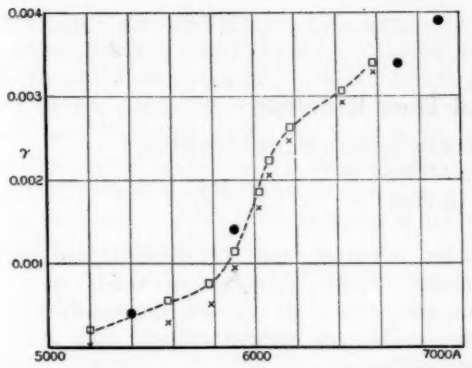


FIG. 3. Absorption coefficient of water for visible light; crosses, uncorrected values of Aufsess;[7] squares and broken line, corrected values; dots from Table II.

this with $\gamma = 0.00002$ as observed by Aufsess[7] it appeared that molecular scattering accounted for practically the entire absorption of water in this spectral region. However, Martin[8] pointed out that Aufsess had not corrected completely for reflection from the end plates of the tube, and when this was done the effect was to increase Aufsess' value about 8 times, which removed it considerably from the theoretical scattering value. For comparison with the ultraviolet results the molecular scattering coefficient $\alpha$ is plotted in curves 2 and 2′, Fig. 2, and is seen to be less than $\gamma$, the ratio $\gamma/\alpha$ being greater than 10. It appears that, although the molecular scattering formula gives a $\gamma$, $\lambda$ curve, $\lambda$ being the wave-length of the light, in the ultraviolet of somewhere near the correct form, it yields values of from 10 to 20 times less than those observed.

It was of interest to determine $\gamma$ in the visible region of the spectrum in order to obtain a comparison with the measurements of Aufsess.[7] For this purpose a sheet of ground glass was placed at *g*, Fig. 1, evenly illuminated by a tungsten lamp at *s*, and *e*, *f* and *r* were replaced by suitable diaphragms. The observer from position *p*, Fig. 1, saw the ground glass through the two tubes *h* and *k* simultaneously as two round spots of light, the spot through the short 0.3 cm tube *k* being in general slightly brighter than that through the long tube *h*, 272 cm in length.

A neutral wedge was passed in front of the short tube and adjusted until the two spots were equal in intensity. From the known transmission of the wedge $\gamma$ was determined. With color filters over the lamp the values of $\gamma$ given in Table II were obtained, the measurement for yellow light 5890A being made with a sodium lamp at *s*.

TABLE II.

| Wave-length | $\gamma$ |
|---|---|
| 5400A | 0.0004 |
| 5890 | 0.0014 |
| 6700 | 0.0034 |
| 6900 | 0.0039 |

The values are plotted as dots in Fig. 3. In the figure the crosses are the original values recorded by Aufsess,[7] and the squares joined by the broken line are the crosses corrected by calculation for the reflection of the glass end-plates of Aufsess's tube, assuming that the refractive index of the glass was 1.5. It is seen that the dots and squares are in good agreement.

For wave-lengths from about 4000 to 5200A water was so transparent that the absorption could not be determined with the 272 cm tube. At the present time there exist no accurate measurements of $\gamma$ in this region, for no one has ever used tubes sufficiently long. $\gamma$ is probably below 0.0004 for blue and green light and to measure the absorption satisfactorily would require tubes at least as long as 10 meters.

[7] Aufsess, Ann. d. Physik **13**, 678 (1904).
[8] Martin, J. Phys. Chem. **26**, 471 (1922).

# Ultraviolet Sources and Their Radiation

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(Received May 14, 1934)

ULTRAVIOLET radiation may be divided into three parts; i.e., the near ultraviolet, middle ultraviolet and the far ultraviolet. The boundaries of these three regions are rather arbitrary but the near ultraviolet region may be considered to extend from wave-length 4000 to 3135A, the middle region from 3135 to 2700A, and the far ultraviolet region from 2700A to shorter wave-lengths. The radiation from the middle region has been found to have value in the treatment of certain diseases such as rickets and is supposed by some to be valuable in the promotion of growth and health. Not a great deal is known as to the effectiveness of the energy of different wave-lengths for various therapeutic purposes, but what little is known seems to show that there is some relation between the therapeutic effectiveness of ultraviolet radiation and its effectiveness in producing erythema. Dr. Maughan[1] has shown that radiation of about the same wave-length interval that is effective in producing erythema is also effective in curing rickets in chickens. It has also been shown that radiation which has passed through ordinary window glass is not effective for such purposes and it is known that ordinary window glass transmits very little radiation of wave-lengths shorter than 3135A. Radiation in the far ultraviolet region is harmful if much of it falls on a person's eyes. However, with proper safe-guards radiation from this region may be valuable in medical practice.

There are a number of different types of sources available for production of ultraviolet radiation for various purposes. Two characteristics of the radiation from these ultraviolet sources which are of interest are the total amount of radiation in a particular region and the spectral distribution of the radiation within that region. Common sources for producing ultraviolet radiation may be divided into three general classes: incandescent solids such as tungsten, arcs in air between such substances as pure carbon or treated carbon, and arcs in mercury vapor.

The sun is sometimes taken as the standard of ultraviolet radiation, the radiation from the other sources being compared with that from the sun both in total amount and in spectral distribution. Quite a number of studies have been made of the spectral distribution of the radiation from the sun. Abbot,[2] Fabry and Buisson,[3] Brian O'Brien,[4] Greider and Downes,[5] Pettit[6] and others have studied the spectral distribution and Coblentz[7] has done considerable work in measuring the total amount of energy of wave-lengths shorter than 3130A. From Pettit's work, the total amount of ultraviolet radiation for wave-lengths shorter than 3130A is found to be about 140 microwatts per square centimeter for mid-day sun in June at Tucson, Arizona. Coblentz gives a figure of 91 microwatts per square centimeter for the radiation from the sun on a clear day in June at noon for Washington which agrees well with the value given by Pettit when one considers the different atmospheric conditions. As a result of all this work, a value of 91 microwatts per square centimeter is accepted as the intensity of the radiation from the sun for wave-lengths shorter than 3130A for the latitude of Washington in the middle of a day in June. This is somewhat more than that obtained from the data of

[1] Maughan, Am. J. Physiol. **87**, 381 (1928).

[2] Abbot, Smithsonian Miscellaneous Collection **74**, 15 (1923).

[3] Fabry and Buisson, Comptes Rendus **175**, 156 (1922); Astrophys. J. **54**, 297 (1921).

[4] O'Brien, Phys. Rev. **36**, 381 (1930).

[5] Greider and Downes, Trans. Ill. Eng. Soc. **25**, 378 (1930).

[6] Pettit, Astrophys. J. **75**, 185 (1932).

[7] Coblentz, Bur. Standards J. Research **6**, 951 (1931).

Abbot and Fabry and Buisson by computation.[8] Coblentz has also shown, both by computation and by experiment, that the erythemal effectiveness of the sun's ultraviolet radiation shorter than and including 3130A at Washington is about 22 percent, that is, it is about 22 percent as effective in producing erythema as if this same total amount of energy were radiated at wave-lengths very near 2967A.

One of the first sources used for the artificial production of ultraviolet radiation was the quartz mercury arc. This is a very intense source because the mercury arc has a number of very strong lines in the middle and far ultraviolet regions and quartz glass has a very high transmission for radiation of wave-lengths greater than 2500A. During the past few years several new sources for the production of ultraviolet radiation in the middle region have been introduced. Data have been obtained on a number of these new sources and will be presented in this paper. In addition, data have been obtained on a quartz mercury arc and are given for comparison.

The particular quartz arc used for comparison was in a fused quartz tube, about 1.5 centimeter in diameter with an arc length of 8.5 centimeters. It was mounted in a holder and protected just enough for the mercury to reach the proper temperature so that the arc would have 75 volts drop when operated at 3.75 amperes. For measuring the distribution of energy our large quartz double monochromator was used. The values obtained for the intensities of the stronger lines of wave-lengths less than 3135A are given in column 2 of Table I. These values are for the arc alone.

The distribution of ultraviolet radiation in the spectrum of the S–1 sunlamp was measured in a similar manner. The reflector was representative of those used in regular practice. The axis of the lamp was tilted 30° from vertical and the measurements made at 76 centimeters (30 inches) from the center of the lamp on the axis of the unit. The ultraviolet output of any of these mercury arcs depends on the temperature of the mercury. The latter depends upon how the lamp is protected from air currents by the socket and reflector and on the tilt of the reflector.

[8] J.O.S.A. 20, 396 (1930).

TABLE I. *Intensities of principal lines of wave-lengths less than 3135A from several ultraviolet sources. (Micro-watts per cm² 30" from source.)*

| | Quartz mercury arc† | S–1 unit* | S–2 unit* | G–5 unit* | G–1 unit* |
|---|---|---|---|---|---|
| Volts..... | 75 | 12.2 | 11.4 | 15.8 | 16.1 |
| Amperes.. | 3.75 | 28.7 | 9.1 | 5.0 | 2.00 |
| Wave-length | | | | | |
| 2483 | 16.2 | | | | |
| 2537 | 55. | 0.2 | 0.1 | | 0.05 |
| 2576 | 7.0 | | | | |
| 2652 | 40. | 0.6 | 0.4 | 0.1 | 0.02 |
| 2699 | 8.0 | | | | |
| 2753 | 6.0 | | | | |
| 2804 | 18.7 | 2.6 | 0.8 | 0.2 | 0.04 |
| 2894 | 9.8 | 4.0 | 1.2 | 0.9 | 0.02 |
| 2925 | 3.3 | | | | |
| 2967 | 27.0 | 19.9 | 5.0 | 3.6 | 0.7 |
| 3022 | 54. | 49. | 10.2 | 2.2 | 0.7 |
| 3129 | 122. | 180. | 36.4 | 21.4 | 5.9 |

† No reflector.
* Energy flux density on axis of reflector. Reflector axis 30° from vertical.

The distribution of ultraviolet radiation about the unit, the effect upon the output of tilting the reflector at different angles and the variation of the ultraviolet radiation with the distance from the arc were determined by using as a measuring device a sodium photo-tube in a quartz bulb with filters to separate the radiation in the middle region from that of longer wave-lengths. This gave an integral value of the radiation for wave-lengths shorter than 3135A which has been shown to agree for like sources with values obtained by summing the line intensities. The spectral intensities, which are the average of values obtained on quite a number of S–1 lamps, are given in column 3 of Table I and the distributions are shown by curves 1 and 2.

Similar measurements were made on the S–2 sunlamp which is quite similar to the S–1 except that it is smaller in size. The spectral intensities of the lines of wave-lengths less than 3135A radiated by this source are given in column 4 of Table I and the distribution shown by curves 3 and 4. The ultraviolet radiation from each of these lamps is really from a special mercury arc since these lamps consist of a mercury arc between hot tungsten electrodes. The hot tungsten electrodes contribute a small amount of the radiation even in the ultraviolet

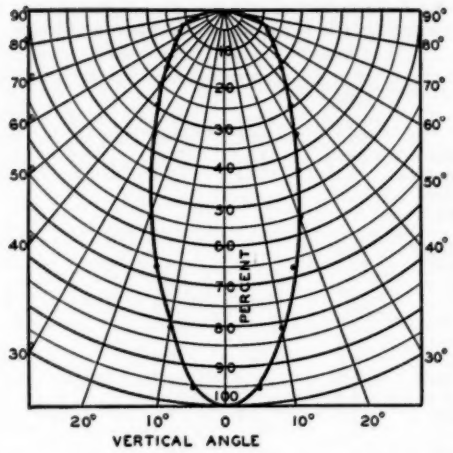


FIG. 1. Distribution in a vertical plane of the ultraviolet radiation from a standard S–1 unit.

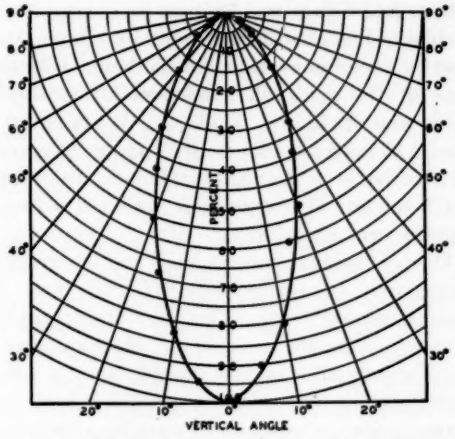


FIG. 3. Distribution in a vertical plane of the ultraviolet radiation from a standard S–2 unit.

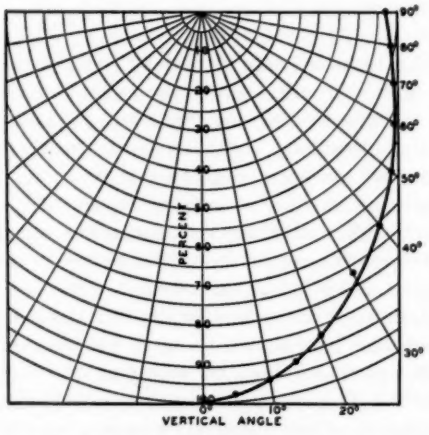


FIG. 2. Variation of the ultraviolet output from a type S–1 unit as the unit is rotated about a horizontal axis. Photo-tube on axis of reflector.

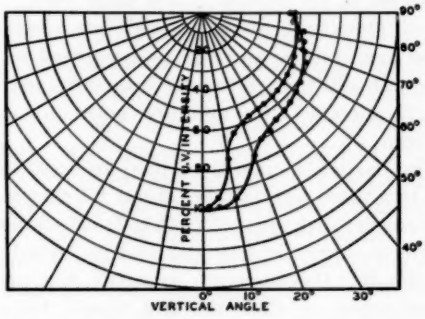


FIG. 4. Variation of the ultraviolet output from an S–2 unit as the unit is rotated about a horizontal axis. Photo-tube on axis of reflector. ○, plane of leads parallel to axis of rotation. ●, plane of leads perpendicular to axis of rotation.

but in the case of these two lamps it amounts to less than 1 percent of the total ultraviolet radiation for wave-lengths shorter than 3135A. Both of these lamps are what may be called high pressure mercury arcs since they operate at a high temperature, the mercury in these lamps having been found to range from 250 to 300°C.

A new source of ultraviolet radiation which has been described[9] and put on the market is a low pressure mercury arc. The discharge takes place between two hot electrodes similar to those used in some vacuum tubes. This lamp operates at a temperature of about 60 to 70°C when it is in the unit. If the lamp is made with a bulb having suitable transmission and the radiation is measured with the lamp in the open where it operates at a relatively low temperature the radiation of the line of wave-length 2537A is very intense. It is, in fact, a major part of the ultraviolet output. As generally used, these lamps are mounted in a glass bulb that has a very low transmission for wave-lengths shorter than 2700A so that the very short radiation is eliminated. There are two lamps of this type, the G–1 and the G–5, the only difference being that the first lamp operates on about 2 amperes

[9] Marden and Nicholson, Trans. I.E.S. 26, 592 (1931).

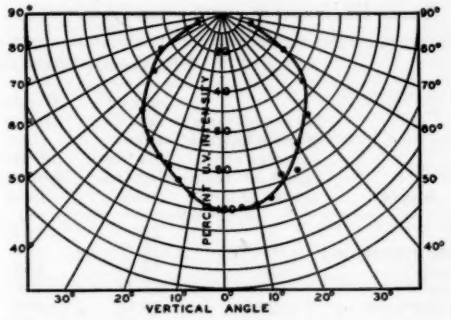


FIG. 5. Distribution in a vertical plane of the ultraviolet radiation from a G–1 unit.

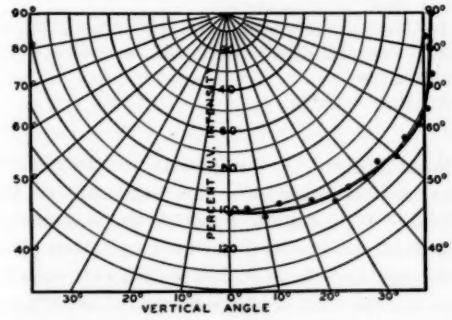


FIG. 6. Variation of the ultraviolet output from a G–1 unit as the unit is rotated about a horizontal axis. Phototube on axis of reflector.

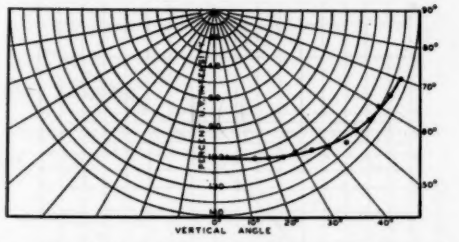


FIG. 7. Variation of the ultraviolet output from a G–5 unit as the unit is rotated about a horizontal axis. Phototube on axis of reflector.

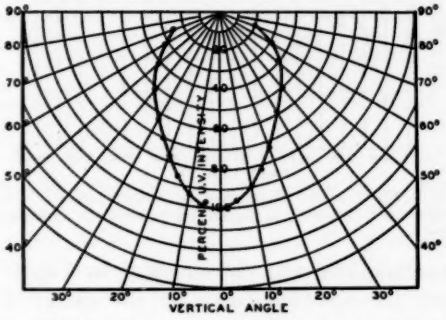


FIG. 8. Distribution in a vertical plane of the ultraviolet radiation from a G–5 unit.

TABLE II. *Variation of the axial intensity of the ultraviolet radiation with the distance from the unit.*

| Distance from lamp electrodes | Variation if inverse square law holds | S–1 | S–2 | G–1 | G–5 |
|---|---|---|---|---|---|
| 1.5 feet | 278. | 287. | 268. | 324. | 317. |
| 2. | 156. | 167. | 152. | 165. | 167. |
| 2.5 | 100. | 100. | 100. | 100. | 100. |
| 3. | 69. | 66. | 66. | 65. | 65. |
| 4. | 39. | 37. | 38. | 34. | 33. |
| 5. | 25. | 24. | 24. | | |

with about 16 volts drop across the lamp and the other, which is larger, operates on 5 amperes and 16 volts. The radiation from each of these lamps in a reflector has been measured in exactly the same way as that from the S–1 and S–2 units. The intensities of the various lines of wave-lengths shorter than 3135A are shown in columns 5 and 6 of Table I and the distribution about the units is shown in curves 5 to 8. There has been a marked improvement in the manufacture of these G lamps during the past year with the result that the amount of ultraviolet radiation from both lamps is considerably greater than it was formerly.

The variations for these different sources of the intensity of the ultraviolet radiation as a function of the distance from the lamp in the unit are shown in Table II.

The Mazda CX tungsten lamp has a bulb with high transmission for ultraviolet radiation. It is intended for the production of intense infra-red radiation combined with a mild ultraviolet radiation. Any source that owes its radiation to temperature alone radiates a very small percentage of its energy at these short wave-lengths unless it is at a very high temperature. Calculation based upon the known properties of tungsten was made of the spectral distribution of the ultraviolet radiation from certain 500 watt CX lamps and the spectral distribution from these same lamps was measured with a large double

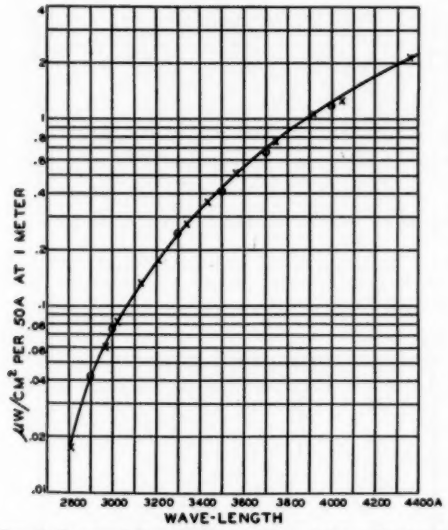


FIG. 9. Spectral distribution of ultraviolet radiation from a 500 watt CX lamp. x, measured points. ⊙, calculated points.

monochromator and thermopile.[10] In Fig. 9 is shown the observed curve for the energy distribution in the spectrum of the 500 watt Mazda CX lamp and for comparison the calculated points are plotted. A very good agreement is shown for radiation of wave-lengths between 2700 and 4000A.

In Table III is given the total amount of ultraviolet radiation for wave-lengths shorter than 3135A in the spectra of these various sources. For comparing these values all are given for a distance of 76 centimeters (30 inches) from the source. Also for comparison, the relative effectiveness of the radiation from different sources in producing erythema has been calculated by using the erythemal effectiveness figures given by Coblentz.[11] It is interesting to compare the amount of erythemal radiation and the total amount of energy of wave-lengths less than 3135A from each of these sources including the sun.

[10] Forsythe and Barnes, R.S.I. **4**, 289 (1933).

[11] Coblenz, Bur. Standards J. Research **12**, 13 (1934).

TABLE III. *Output of several ultraviolet sources.*

| Source | Microwatts/cm² of wave-lengths shorter than 3135A 30″ from center of lamp | Erythemal Ultraviolet: μw/cm² at 30″ times relative effectiveness | Erythemal Ultraviolet: E-vitons in 22″ circle 30″ from center of lamp |
|---|---|---|---|
| Sun | 91. | 20. | 4900 |
| Quartz mercury arc | 400.** | 134.** | |
| S–1 unit* | 260.† | 54.† | 8500 |
| S–2 unit* | 55.† | 12.2† | 1920 |
| G–5 unit* | 29.† | 5.7† | 1160 |
| G–1 unit* | 7.4† | 1.4† | 260 |
| 500 watt CX lamp | 1.2** | 0.3** | |

* Unit tilted 30° from vertical.

** In direction perpendicular to axis of lamp. No reflector. If a suitable reflector were used these values would be much higher.

† On axis of reflector.

Manufacturers of equipment for furnishing ultraviolet radiation now rate sunlamps of the applicator type on the basis of the amount of erythemally weighted ultraviolet radiation passing through a circle 22 inches in diameter with its center on the axis of the reflector at a distance of 30 inches from the source. The unit of erythemally effective flux has been defined as an amount of ultraviolet flux, which after weighting according to its erythemal effectiveness, is equivalent to 10 microwatts at 2967A. The name E-Viton[12] has been suggested for this unit of equivalent flux. For the unit of flux density one unit of erythemally effective flux per square centimeter has been defined as the Finsen unit.

In Table III are given the ratings of a number of sunlamps in terms of these new units. The rating in this case is the number of E-Vitons in a 22-inch circle at a distance of 76 centimeters (30 inches) from the source. Since these sunlamps are generally tilted to an angle of about 30° when in use, the values given are for the units tilted at this angle.

[12] Luckiesh and Holladay, J.O.S.A. **23**, 197 (1933).

# Portable Ultraviolet Meters

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(Received April 19, 1934)

WAVE-LENGTHS in the ultraviolet spectrum of sunlight and artificial sources between λ3200 and λ4000 (Angstroms) are not known to be either necessary or beneficial to human beings. However, those shorter than λ3200 have been proven beneficial in the cure and prevention of rickets and in the treatment of many disorders of the human body. Erythema[1] (reddening of the skin, sunburn) and tanning are produced principally by wave-lengths shorter than λ3200, hence erythema has come to be considered a reliable "measuring-stick" for beneficial ultraviolet radiation. It has been adopted by the American Medical Association[2] as a basis for comparing the effectiveness of sunlamps.

Since several hours must elapse between exposure to ultraviolet and the production of erythema, there has been a need for an instrument or device which would measure instantaneously the intensity of the ultraviolet from a source, and weight it approximately in proportion to its value in producing erythema. Various investigators, including the present author,[3] have found cadmium photo-cells satisfactory in the appraisal of erythemal ultraviolet radiation. The author and his colleague have previously described[4] a two-stage d.c. amplifier for use with a cadmium photo-cell, since the current obtainable from such a photo-cell is too small for measurement without amplification. The weight of that amplifier, complete with batteries and photo-cell, is approximately 30 pounds. This weight is undesirably high for a portable instrument, although this instrument has proved very satisfactory for field measurements.

About a year ago we built a new type d.c. amplifier. In developing this amplifier, which will be described in this article, the main object was to produce a simple instrument which would maintain its calibration for a long period of time and which would be small, light and easily portable. The result has been an instrument weighing only 12 pounds complete. It is contained in a portable case approximately $7\frac{1}{2} \times 9\frac{1}{2} \times 7$ inches.

Fig. 1A is a simplified wiring diagram of the *indicating* ultraviolet meter, while 1B is a similar diagram for an *integrating* meter which will also be described. When not in use the photo-cell is placed inside the portable case and when in use

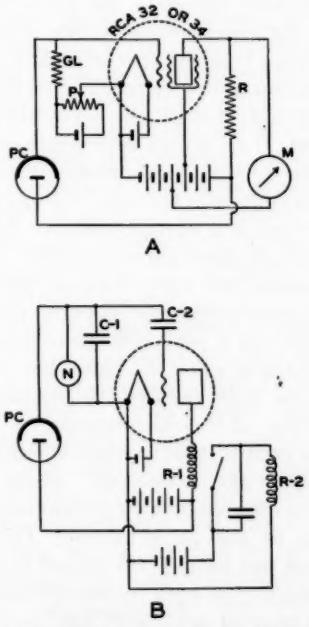


FIG. 1. Simplified wiring diagrams for (A) *indicating* and (B) *integrating* ultraviolet meters. *PC*, photo-cell; *GL*, grid leak; *P*, potentiometer; *R*, resistance; *M*, microammeter; *N*, small neon lamp; *C*−1 and *C*−2, fixed condensers; *R*−1, sensitive relay; *R*−2, relay of the message counter type.

[1] M. Luckiesh, *Artificial Sunlight*, D. Van Nostrand Co., New York, 1930.

[2] J. Am. Med. Assoc., p. 1863, June 10, 1933.

[3] A. H. Taylor, *Measurement of Erythemal Ultraviolet Radiation*, J. Opt. Soc. Am. **23**, 60 (1933).

[4] A. H. Taylor and G. P. Kerr, *A Direct-Current Amplifier with Good Operating Characteristics*, Rev. Sci. Inst. **4**, 28 (1933).

a polarized plug is plugged into the back of the case. The photo-cell cable and the meter case are electrically shielded, the shield being grounded to the negative filament of the vacuum tube.

This meter employs an RCA32 or 34 vacuum tube. The normal rating of the filament of these tubes is 0.06 ampere at 2.0 volts, but in this meter it is operated at 0.05 ampere, hence the life should be quite long, barring accidental breakage or burnout.

A microammeter, $M$ (full scale 30 microamperes), measures the change in plate current when the photo-cell is radiated. By means of the potentiometer, $P$, in the grid circuit, it can be made to read zero when the photo-cell is covered. The microammeter can be made to read $\frac{1}{2}$ or $\frac{1}{4}$ scale, thus extending the range of intensities over which it can be used. A switch, not shown in the diagram, selects one of a number of grid leaks in the control grid circuit, and by this means the sensitivity of the meter can be varied over a range of about 550 to 1.

The 45 volt plate battery furnishes voltage for the screen grid, the plate, the photo-cell and to balance the microammeter. In view of its multiple uses it might appear at first sight that any reduction in the voltage of this battery due to use would change the calibration of the instrument. If a vacuum type photo-cell is used, its response to a constant amount of radiation is not appreciably affected by a voltage reduction of 10 percent in a 45-volt battery. An analysis of grid voltage-plate current curves for RCA32 and 34 radiotrons under various conditions of operation shows that the slope of the straight line portion, for a plate voltage of 45, is practically unchanged when the plate and screen grid voltages are both reduced 10 percent. Hence, the deflection of the microammeter for a given change in control grid voltage (brought about by radiating the photo-cell) would not be appreciably affected by a 10 percent depreciation in voltage of the plate battery. The current drawn from this battery is so small that the life of the battery, even with considerable use, would be almost as great as its shelf life.

The *integrating* ultraviolet meter has been designed for application in fields such as the measurement of the ultraviolet in daylight, the total radiation received by individuals exposed to ultraviolet sources, the irradiation of chemicals and foodstuffs, etc. It should prove to be a valuable tool in quantitative studies of the effects of ultraviolet in industrial processes.

The integrating meter employs the principle of charging a small condenser, $C-1$, in series with a photo-cell, $PC$, discharging it through a small neon lamp, $N$, and recording the number of discharges over a period of time. This method of flashing a neon lamp, employing a series resistance instead of the photo-cell, has been previously described by Moore.[5] Rentschler[6] has employed a special type of grid-glow tube in an ultraviolet meter by using a uranium photo-cell, the number of discharges in any period of time being recorded by a counting relay.

In the present meter the discharge of the condenser, $C-1$, through the neon lamp, $N$, reduces the plate current of a 3-element vacuum tube. This closes the contacts of a sensitive relay in the plate circuit, which in turn actuates two other relays, the second of which is of the message-counter type. This registers the number of discharges. This counter can also be made to flash a small tungsten lamp, thus giving a visible signal for demonstration purposes. The sensitivity of the meter can be varied over a range of approximately 15 to 1.

In both of these meters the quantity measured depends upon the spectral sensitivity of the photo-cell used. For the measurement of the power of a source to produce erythema, cadmium or cadmium alloy photo-cells appear to be most useful. With a cell of this type the indicating meter can be calibrated to read in erythemal vitons (E-vitons)[7] per square centimeter. The integrating meter can be calibrated in terms of E-viton hours or some related unit.

The same meters can be used to measure low intensities of light, if a caesium oxide photo-cell is used. With the indicating type meter and a caesium photo-cell a full scale reading was obtained with an illumination of approximately 0.001 footcandle.

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[5] D. M. Moore and L. C. Porter, *Recent Developments of Moore Gaseous Conductor Lamps*, Trans. I.E.S. **21**, 176 (1926).

[6] H. C. Rentschler, *An Ultraviolet Light Meter*, Proc. A.I.E.E. **49**, 113 (1930); Trans. I.E.S. **25**, 406 (1930).

[7] M. Luckiesh and L. L. Holladay, *Fundamental Units and Terms for Biologically-Effective Radiation*, J. Opt. Soc. Am. **23**, 197 (1933).

# Heat as an Agent for the Production of the Latent Photographic Image

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AND
PHILIP A. LEIGHTON, *Department of Chemistry, Stanford University*

(Received March 12, 1934)

BELLIOT[1] subjected exposed and unexposed photographic emulsions to heat and then developed them. From his observations he concluded: (1) that the density of a plate previously exposed to light is lowered under the action of heat, (2) that heat caused the density of an unexposed emulsion to increase, (3) that emulsions where the first image is partially destroyed by heat become again sensitive after the action of heat, (4) that the sensitivity thus restored is less than the original sensitivity. A possible explanation of these findings will become apparent in the discussion which follows.

Several reports exist in the literature on the effect of temperature upon the sensitivity of a photographic emulsion to light. In one of these[2] Baker and Balmain state that the heating of the plates during exposure was in no case found to give an increase in fog even at the boiling point of water.

Carroll, Hubbard and Kretchman have recently presented a paper[3] on the stability of finished plates. This paper will be considered in connection with other related data which will be published later.

In the following report the results of a study of heat as an agent for the production of developable densities are presented.

## The Rate of Formation of Developable Density by Heat

In order to determine the characteristics of the production of a developable density by heat, Eastman lantern slide plates of the regular grade were heated at various temperatures and for various intervals in an electric oven which was held closely to any desired temperature by means of a mercury regulator. It is known that the stability of emulsions to heat depends upon the conditions of their preparation. The plates were supported in a holder consisting of a series of 1/8″ brass sheets, large enough totally to enclose the photographic plates, and clamped together with "spacers" leaving room for one plate between each two sheets of brass. The intervals required for the plates to attain the temperature of the oven were determined by placing one junction of a thermocouple in contact with a plate as it was placed in the holder, the other junction being maintained at the oven temperature. These intervals were found to be small when compared with the exposures usually given, but where necessary a correction was made in the recorded time of heating.

After the plates were exposed to heat for the desired time they were removed, rapidly cooled, and then developed for three minutes at a temperature of 21°C in developer 73 (of the Eastman Kodak Company) diluted with four parts of water. They were then rinsed, fixed and dried in the usual manner.

The plates were not exposed to light at any time either before, during, or after the heating process, so that the only latent image or developable density which existed on them was due to the exposure to heat.

High developable densities were produced by considerable exposures to heat, and except at the lower temperatures, the densities were as uniform over various parts of the plates as are those produced by uniform exposure to light. At lower temperatures the developable density varied over the surface of the plate, resulting in a mottled appearance resembling very much the "mealy" effect produced by the aging of an emulsion.

[1] Belliot, Comptes Rendus **183**, 1279 (1926).
[2] Baker and Balmain, Proc. Seventh Int. Cong. Phot. 42 (1928).
[3] Carroll, Hubbard and Kretchman, Bur. Standards J. Research, **12**, 223 (1934).

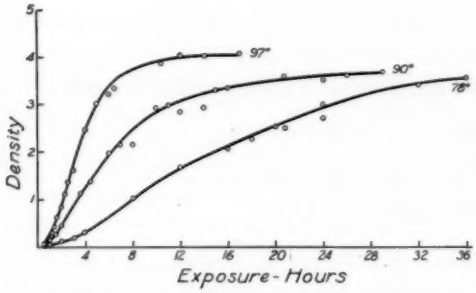


FIG. 1. The developable density produced by exposure to heat is plotted against the time of exposure. The temperatures at which the plates were exposed are indicated.

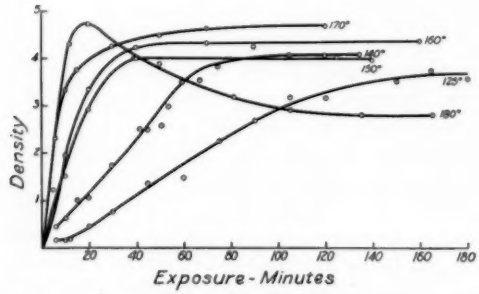


FIG. 2. The developable density produced by exposure to heat is plotted against the time of exposure. The temperatures at which the plates were exposed are indicated.

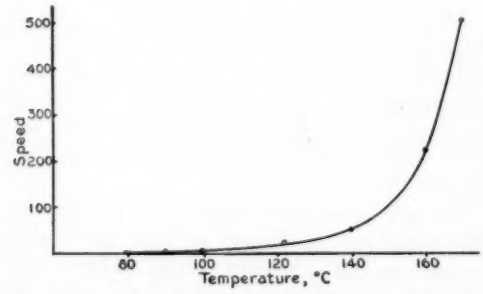


FIG. 3. The "speed" of plates to heat at various temperatures arbitrarially assuming the "speed" of the plate at 63° to be 1.

After development, the densities obtained were measured in a specially constructed densitometer in which the plate to be measured was set between a 500 watt projection lamp and a Moll surface thermopile. Due precautions were taken.

The developable densities produced by various times of exposure to different temperatures are shown in Figs. 1 and 2. These curves are strikingly similar to the density-time curves obtained for exposures to light. Density reduction by continued exposure (the equivalent of solarization by light) was not found to occur at temperatures below 170°C, although it was pronounced at 180°C and above. When, at temperatures below 170°C, the maximum developable density had been attained, excessive added exposure produced no appreciable change.

The close resemblance between the density-time curves for exposure to heat and to light suggested the possibility of obtaining a quantity for exposure to heat analogous to the Hurter and Driffield "speeds" for exposure to light. Plotting the densities of Figs. 1 and 2 against the logarithm of the time, determining the intercepts of the straight line portions, assuming the "speeds" at various temperatures are inversely proportional to the antilogarithm of these intercepts, and arbitrarily setting the "speed" at the lowest temperature, 63°C, at 1, the speeds to heat at other temperatures were determined as shown in Fig. 3.

The differential equation

$$dx/dt = k_1 x^{\frac{1}{2}}(b-x) - k_2 x$$

developed by the authors[4] for the rate of formation of the latent image by light, may be applied to the data of Figs. 1 and 2 to obtain the rates of the reactions concerned in the production of the latent image by heat. In the above equation, $k_1$ and $k_2$ are the velocity constants for the forward and reverse reactions, $x$ is the developable density existing after time of exposure $t$, and $b$ is the ideal maximum developable density (6.8). No correction need be made for the "buried" grains as is the case for exposure to light, since all of the grains were at the same temperature, hence equally exposed. The values of the velocity constants, $k_1$ and $k_2$ were determined in the manner described in the earlier paper,[4] and are given in Table I. The mean temperature coefficient of the forward reaction over the range 78–170°C is 1.8; that of the reverse reaction is 1.7. The absence of composite reactions is indicated by the straight lines obtained by plotting log $k$ against $1/T$, Fig. 4. The slopes of these lines correspond to an

[4] Blair and Leighton, J. Phys. Chem. 36, 1649 (1932).

TABLE I. *Forward ($k_1$) and reverse ($k_2$) reaction velocity constants.*

| Temperature | $k_1$ | $k_2$ | $k_1/k_2$ | Maximum developable density |
|---|---|---|---|---|
| 78°C | 0.0399 | 0.0616 | 0.65 | 3.8 |
| 90 | .0705 | .11 | .64 | 3.8 |
| 97 | .159 | .223 | .71 | 4.0 |
| 125 | .48 | .672 | .71 | 4.0 |
| 140 | 1.41 | 1.97 | .71 | 4.0 |
| 150 | 1.71 | 2.4 | .71 | 4.0 |
| 160 | 2.46 | 2.9 | .85 | 4.3 |
| 170 | 4.33 | 4.4 | .98 | 4.6 |
| 180 | — | — | 1.09 | 4.8 |
| 190 | — | — | 1.25 | 5.0 |

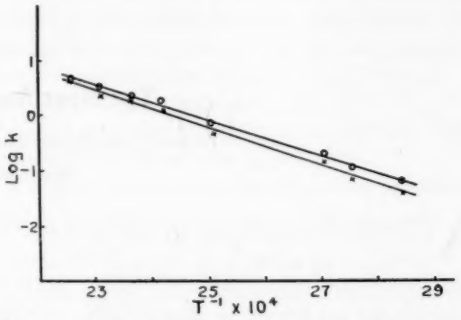


FIG. 4. Showing the relation between the forward (crosses) and the reverse (circles) reaction velocity constants and the reciprocal of the absolute temperature.

energy of activation, for both reactions, of about 15,000 calories/mole.

It is interesting and possibly significant that only those temperatures at which the ratio $k_1/k_2$ became greater than 1 was any solarization or reduction in density by continued exposure to heat, observed. The criteria usually applied indicate that the heat of reaction and free energy change involved in the formation of developable grains by heat are small.

## A COMPARISON OF THE EFFECTS OF HEAT AND LIGHT

The essential similarity between the developable densities or latent images produced by heat and light is evidenced by the fact that they react to the same developing agents; the similarity of the density-time curves; the successful application of the same rate equation to both processes; the fact that the maximum developable density increases with temperature as it does with light intensity; the appearance of solarization at high temperatures and high light intensities; and the similar behavior of heat and light images during the period between exposure and development. The application of the rate equation to combined exposures to light and heat showed that the two effects are additive, the rate of increase of developable density being approximately the same whether the density up to that time had been produced by heat or light.

As additional evidences for this similarity, it may be cited that latent images produced by heat are subject to physical development in the same manner as are those produced by light; heat images are destroyed by treatment with chromic acid as are light images; and the halogens destroy the sensitivity of the dry emulsion to heat as they do to light, this effect being greatly diminished in both cases if the emulsion is wet when the halogen is present.

On the other hand, chromic sulfate (*vide supra*) was found to act as a sensitizer to heat, but not to light, and the desensitizers, pinakryptol yellow and pinakryptol green, which are effective for light are without marked effect on the rate of production of developable density by heat.

# The Specification of Whiteness

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(Received May 12, 1934)

ALTHOUGH a complete specification of color requires in general at least three parameters, there are many industrial color problems in which one parameter is substantially constant. This is likely to be true in the case of nearly white materials such as cotton, paper and many similar articles of commerce. The dominant wave-length of such materials is frequently in the neighborhood of 575 mμ and remains approximately constant despite variations in the brightness and purity. It is common practice to grade such materials according to "whiteness," a term which is used by color graders to denote the closeness with which the sample approaches a pure white. Evidently such samples may differ from a pure white in two respects; the brightness (reflectance) may be less than 100 percent or the purity may be greater than zero. Thus, a color grader may consider that a sample with a reflectance of 75 percent and a purity of 2 percent looks as white as another sample having a reflectance of 85 percent and a purity of 4 percent. In arriving at this conclusion, he unconsciously demands that the second sample have a higher reflectance to offset its greater proportion of yellow. The purpose of this article is to present the results of an attempt to correlate the color grader's concept of whiteness with the objectively determinable quantities—brightness and purity—in the case of materials having a constant dominant wave-length of 575 mμ.

Briefly, the procedure adopted was as follows: A large number of samples were prepared which exhibited variations in brightness and purity only. The spectral reflectance curves of these samples were determined with a spectrophotometer and the dominant wave-length, brightness and purity of each were computed. The samples were then submitted to a group of observers, who were instructed individually to arrange the samples in the order of their whiteness. The resulting arrangements were analyzed by a statistical method and correlated with the objective measurements. This correlation makes possible the prediction of the most probable whiteness arrangement of any set of similar samples from their spectrophotometric data.

## EXPERIMENTAL PROCEDURE

The samples used in these experiments were pieces of white cotton cloth about 24 inches wide and 36 inches long, folded into pads 6 by 9 inches exposing central portions of the cloth to view. Thirty-six such samples were prepared with varying degrees of brightness and yellowness by altering the laundering process. Previous measurements on similar cloths had indicated that, although there were variations over the ranges from 80 percent to 95 percent in the brightness and from zero to 10 percent in the purity, the dominant wave-length was in every case between 574 and 576 mμ. In order to extend the range of the tests, very small amounts of iron salts and of carbon black were added to some of the laundering baths to increase the purity and decrease the brightness beyond the ranges ordinarily attained. Such treatment was such as to conserve the dominant wave-length.

These 36 cloth samples were analyzed on the recording photoelectric spectrophotometer at the Massachusetts Institute of Technology. This instrument was designed and built under the direction of Professor A. C. Hardy, by whom it was described at the February, 1934 meeting of the Optical Society of America. This is a null instrument in the strictest sense and measures the diffuse reflectance for normally incident light. Four representative curves (redrawn on a reduced scale) are shown in Fig. 1. The reflectance values are relative to a freshly prepared opaque layer of magnesium oxide deposited on a block of magnesium carbonate. The greatest uncertainty in the indicated values of reflectance

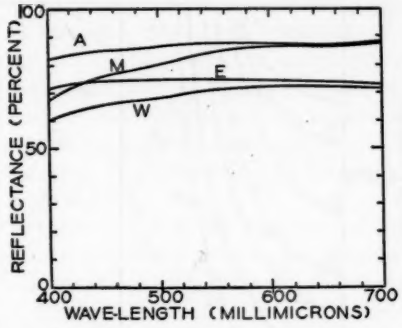


FIG. 1. Representative spectrophotometric curves of white cloth samples. Indicated reflectance values are relative to magnesium oxide.

is less than 0.5 percent and the differences between values determined several weeks apart is less than half this figure.

The dominant wave-length, brightness and purity were computed according to the 1931 I.C.I. data, by using Illuminant *C*.[1] The three necessary integrations were performed by the selected ordinate method. In this method each integral is computed by the summation of the reflectance values of the sample at a number of selected wave-lengths which depend on the appropriate I.C.I. function and the desired illuminant. Denoting the values of these integrals by $X$, $Y$, $Z$, the coordinates of the point representing the sample on the color mixture diagram are

$$x = X/(X+Y+Z),$$

$$y = Y/(X+Y+Z).$$

The brightness is a known fraction of the value of $Y$. The dominant wave-length was determined graphically as that of the point on the spectrum locus collinear with the points representing Illuminant *C* and the sample on the color mixture diagram. For extensive work with many samples in a restricted range of colors, it is expeditious to draw a large scale section of the color mixture diagram. The 36 samples prepared for this test are represented on such a diagram (Fig. 2) from which the dominant wave-length and purity may be read to sufficient accuracy.

As previously mentioned the dominant wave-length of all the samples is within one millimicron of 575 mμ. The two remaining parameters, purity and brightness, were used for a two dimensional representation of the 36 samples. Twenty-four of these samples were selected so as to cover uniformly the region of interest. This region is from 70 to 90 percent in brightness and from 0 to 10 percent in purity.

A visual classification test was then arranged. A room was selected on the top floor of a building high enough to avoid reflection from neighboring buildings. This room had white walls and a northern exposure through large windows. The tests were carried out on completely overcast days and the samples were placed on a long table covered with a black cloth. Thirty observers were employed, each working independently. These individuals were questioned as to color blindness and a few were excused because of some doubt as to their normalcy. No specific test for abnormality was employed. There were equal numbers of men and women in the group, most of whom were accustomed to the daily handling and judgment of white samples. The pile of samples was submitted in random arrangement to each observer, who was instructed to arrange them in order of whiteness according to his best judgment. It was immediately evident that there was little if any detailed consistency in the arrangements submitted by various observers. A repetition of the test after a six-weeks interval, with ten of the original observers, revealed that no observer could repro-

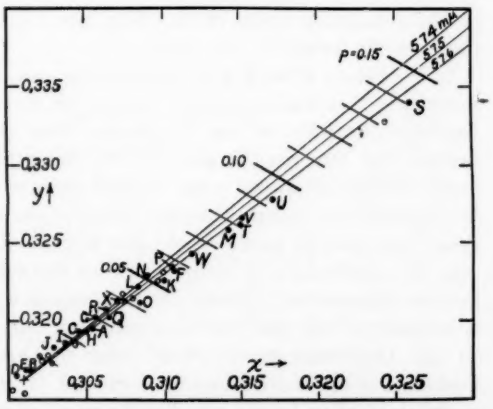


FIG. 2. Representation of thirty-six white cloth samples on an enlarged section of the I.C.I. color mixture diagram. Letters indicate the twenty-four samples chosen for the visual tests.

[1] D. B. Judd, *The 1931 I.C.I. Standard Observer and Coordinate System for Colorimetry*, J.O.S.A. **23**, 359 (1933).

duce his original arrangement noticeably better than he could reproduce the arrangement of other observers.

A general consistency was evident in all the arrangements and a statistical study was employed to interpret this. A simple averaging of the place numbers of each sample exhibited some regular correlation with the classification of the samples on the brightness-purity diagram. Studies of the frequency distributions of each sample relative to every other sample in the whiteness arrangements revealed definite groupings which are interpreted as forming classes of equally white samples. Thus the relative arrangement of samples *E*, *G*, *H*, *I* appears quite random when the whiteness arrangements according to various observers are examined. However, these four samples quite commonly are grouped together. Furthermore, they are by unmistakable agreement classed as inferior in whiteness to samples *C* and *D*, and superior to samples *J* and *Q*. Grouping of the samples in this manner was in complete agreement with the results of the simple averaging of place numbers. The additional information that certain groups of samples were equally white as far as a consistent visual grading was concerned permitted the drawing of whiteness contours through the points representing such groups in the brightness-purity diagram. These contours are fairly well defined between 70 and 85 percent in brightness and from 0 to 6 percent in purity. Some data are at hand for the rough extension of the contours in the remaining parts of the diagram. Fig. 3 presents the results of this study.

It is evident from Fig. 3 that in the case of samples of this dominant wave-length, whiteness depends primarily on the brightness when the purities are less than 3 percent. On the other hand, whiteness appears to depend primarily on the purity for samples having a purity greater than 5 percent. It seems reasonable to conclude that the results of any future work on the subjective whiteness of slightly yellow samples will be consistent with the whiteness contours traced on the brightness-purity chart over the area studied. Future work may be expected (1) to establish similar lines and classifications more precisely; (2) to evaluate a truly subjective scale with which to label the whiteness classes;

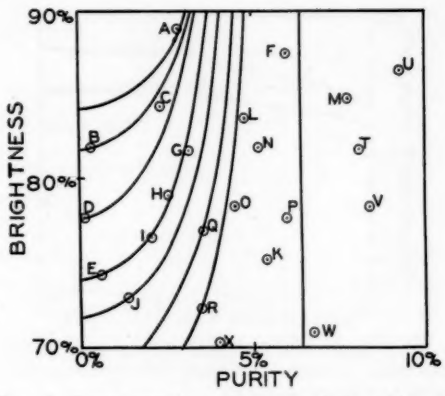


FIG. 3. Representation of twenty-three white cloth samples on the brightness-purity diagram. The indicated whiteness contours were derived from statistical studies of whiteness arrangements by thirty observers.

(3) to extend the lines for other regions of brightness and purity and for other dominant wave-lengths; (4) to determine to what extent the surface characteristics of samples alter the subjective classification.

## SUMMARY

"Whiteness" in the sense in which the term is employed in industry and in popular parlance is an undefined term. In the strictly physical sense, on the other hand, only those colors which have a purity of zero can be called white, and for such colors there is no need for the concept of degree of whiteness, the brightness being a complete specification. In the case of samples which are not white in the physical sense, their color must be described by a specification of the dominant wave-length and purity, in addition to the brightness. Industrial insistence on a single term with which to designate the degree of satisfaction of a customer with materials which are nominally white has resulted in the adoption of the term "whiteness" for this purpose. Much as this is to be regretted in the interest of precise terminology, it is a fact. The best way of endowing the term with a suitably precise meaning is by formulating a definition that will enable it to serve its purpose with facility and precision. A term intended to be used for specification is both meaningless and useless unless a method of measuring the associated quantity is a corollary of the definition of

the term. In order that the term whiteness may serve its purpose, therefore, methods of determining it must be prescribed which will give results consistent with qualitative visual whiteness classifications. Degree of whiteness in such classifications consciously or unconsciously measures the degree of satisfaction with the approach to the ideal white.

One possible method of securing a rapid, precise, and generally consistent measure of whiteness has been investigated and reported here. It has been applied only to a restricted class of samples, and it is evident that any one-parameter whiteness classification must be restricted to the class of samples for which it is devised. An extension of this method of whiteness specification to other classes of samples is feasible and straightforward.

Since the method described above is a straightforward extension of the standardized method of objective color specification, it may be advantageously standardized for the benefit of the many industries which are vitally concerned with whiteness specification.

### Acknowledgment

The author wishes to express his appreciation of Professor A. C. Hardy's interest and assistance during the planning, execution, and interpretation of these experiments.

# Reflection-Factors of Various Materials for Visible and Ultraviolet Radiation

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(Received May 24, 1934)

THE term "reflection factor" has been defined by the Illuminating Engineering Society[1] and the American Engineering Standards Committee as follows: "Reflection factor: The reflection factor of a body is the ratio of the light reflected by the body to the incident light. It is the sum of the regular and the diffuse reflection factors."

Data pertaining to the reflecting properties of various materials for both visible and ultraviolet radiation have been published at various times by numerous authors.[2–7] Some of the measurements have been made by photographic methods, while photoelectric cells have sometimes been employed. In most cases the measurements have been made at definite angles of incidence and reflection, hence the results are not necessarily proportional to the integrated reflection-factors.

In 1920 the present author[8] described a portable reflectometer employing a small integrating sphere to measure reflection-factors for light, and more recently he has described[9] a modification of this reflectometer applicable to the measurement of reflection-factors spectrally in the ultraviolet. Both of these instruments are *absolute* instruments, i.e., no known standards of reflection are necessary. Also, the results obtained are independent of the diffusion characteristics of the surfaces measured.

During the past few years we have measured the reflection-factors of many materials, for both visible and ultraviolet radiation. In particular, a study of aluminum has been made in cooperation with Dr. J. D. Edwards of the Aluminum Company of America. In a paper[10] describing these tests three methods of etching aluminum to obtain high reflection-factors were described. Aluminum sheets as received from the mill can be greatly improved in reflectivity by etching for a short time, or by removal of a thin layer of the surface. In one case a sheet of mill-finished aluminum had its reflection-factor for light from a flashlight lamp changed from 53 to 82 percent by removing a thin layer of the surface on a lathe.

Table I gives reflection-factors for variety of materials. In some cases only a few specimens have been measured; hence in no case should the values be taken as exact for the material. It is believed, however, that in most cases the values given are representative. The reflection-factors in Table I are for the light from a small flashlight tungsten lamp (color temperature approximately 2000°K) and for monochromatic radiation of wave-length 2967 Angstroms. The latter value is of importance as it is in the region of greatest interest in therapeutic applications of ultraviolet radiation. Most of the materials measured are practically non-selective in the visible spectrum.

Probably one of the most important developments in reflecting materials in many years is one recently announced by the Aluminum

[1] *Revised Code of Nomenclature and Standards*, Trans. I.E.S. **23**, 728 (1930).

[2] E. O. Hulburt, *The Reflecting Power of Metals in the Ultraviolet Region of the Spectrum*, Astrophys. J. **42**, 205 (1915).

[3] M. Luckiesh, *Ultraviolet Radiation*, D. Van Nostrand Co., 1922.

[4] Geo. F. A. Stutz, *Observations of Spectro-Photometric Measurements of Paint Vehicles and Pigments in the Ultraviolet*, J. Frank. Inst. **200**, 87 (1925).

[5] M. Luckiesh, *Spectral Reflectances of Common Materials in the Ultraviolet Region*, J. Opt. Soc. Am. and Rev. Sci. Inst. **19**, 1 (1929).

[6] M. Luckiesh, *Artificial Sunlight*, D. Van Nostrand Co., 1930.

[7] M. Luckiesh and L. L. Holladay, *Paints for Reflecting Biologically-Effective Ultraviolet Radiation*, J. Frank. Inst. **212**, 787 (1931).

[8] A. H. Taylor, *A Simple Portable Instrument for Measuring Reflection and Transmission Factors in Absolute Units*, Trans. I.E.S. **15**, 811 (1920).

[9] A. H. Taylor, *The Measurement of Reflection-Factors in the Ultraviolet*, J. Opt. Soc. Am. **21**, 776 (1931).

[10] A. H. Taylor and Junius D. Edwards, *Ultraviolet and Light Reflecting Properties of Aluminum*, J. Opt. Soc. Am. **21**, 677 (1931).

TABLE I. *Reflection-factors of various materials for light from a small tungsten lamp, and at λ2967 in the ultraviolet.*

| Metals | Percent Reflection-Factor For light | At λ2967 |
|---|---|---|
| Aluminum, mill-finish | 53 | 33 |
| Same, surfaced on lathe | 82 | 78 |
| Aluminum, high polish | 72 | 56 |
| Aluminum, etched or oxidized | 75–85 | 65–82 |
| Aluminum A, polished and electrolytically brightened | 87 | 84 |
| Aluminum A, polished, electrolytically brightened and alumilite | 85 | 69 |
| Aluminum-magnesium alloy, polished | 88 | 74 |
| Sputtered aluminum alloy | 95 | 87 |
| Chromium-plated metal | 62–66 | 43–58 |
| Nickel-plated metal | 60–63 | 29–34 |
| Silver-plated metal | 90 | 13 |
| Chrome steel, satin | 56 | .. |
| Chrome steel, polished | 62 | .. |
| Stainless steel | 65 | 30 |
| Rhodium | 70–78 | 45 |
| Eraydo (zinc, silver, copper alloy) | 66 | 52 |
| Allegheny metal | 55–60 | 30–36 |
| Sprayed aluminum (anodic process) | 64 | 65 |
| Sprayed cadmium (anodic process) | 52 | 25 |
| *Water paints* | | |
| Alabastine, white | 76 | 26 |
| Alabastine No. 6, light cream | 74 | 25 |
| Devoe Kalsomine, white | 75 | 35 |
| Sherwin-Williams Decotint, white | 75 | 40 |
| *Miscellaneous* | | |
| Aluminum paint | 75 | 65 |
| White enamelled metal | 65–75 | 5–8 |
| White lead paint, flat | 80 | 27 |
| White plaster | 90 | 50 |
| Magnesium oxide (smoked) | 98 | 95 |
| Magnesium carbonate | 96–98 | 78–80 |
| *Saturday Evening Post* | .. | 21 |
| Newspaper | 50 | 7 |

Research Laboratories of the Aluminum Company of America.[11] They have developed methods of "electrolytically brightening" and "Alumiliteing" aluminum surfaces to produce high reflection-factors. The method is applicable to either highly polished or etched surfaces, and the depreciation[12] of such surfaces under various conditions of use in much lower than that for aluminum surfaces not subjected to the "Alumilite" process of oxidation.

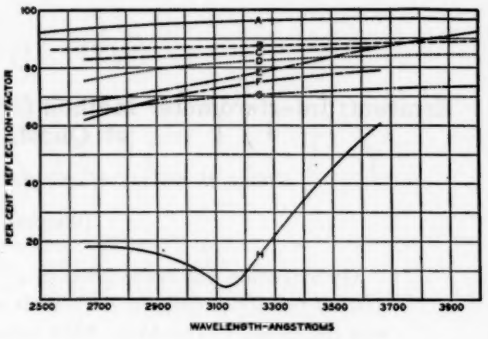


FIG. 1.

Fig. 1 shows spectral reflection curves in the ultraviolet for several types of materials, some of which have very high reflection-factors in this region. Curve *B* in this figure is for a surface of aluminum alloy (probably an alloy of magnesium and aluminum) deposited on glass by sputtering in a high vacuum. It was prepared by Dr. A. Hoyt of the Gulf Research Laboratories.

The author wishes to express his appreciation to Mr. G. P. Kerr of this laboratory, who made most of the reflection-factor measurements.

[11] Junius D. Edwards, *Aluminum for Reflectors*, Trans. I.E.S. **29**, 351 (1934).

[12] A. F. Dickerson, *Tests on Alzak Aluminum Reflectors*, Trans. I.E.S. **29**, 358 (1934).

# Erratum: Interferometer Method for Measuring the Amplitude of Vibration of Quartz Bar Crystals

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(Received May 30, 1934)

My attention has been called to an error in my article entitled *Interferometer Method for Measuring the Amplitude of Vibration of Quartz Bar Crystals* which was published in the May, 1934 issue of the *Journal of the Optical Society of America*.

The table giving the calculated amplitudes in centimeters shows two zeros following the decimal place. There should be three instead of two. For example, the first one listed is 0.0019 cm and it should be 0.00019 cm. Likewise all the rest should have three zeros following the decimal place.